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Dental Effects of Diet and Coca-Leaf Chewing on Two Prehistoric Cultures of Northern Chile

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ABSTRACT Two ancient cultures of northern Chile, the Chinchorro (9000–3500 BP) and the Maitas Chiribaya (850–700 BP) were examined for dental pathology in search of possible correlations between dental health, diet, and the cultural practice of coca-leaf chewing. The Chinchorro occupied the river mouth of the Azapa valley, subsisting almost exclusively on a maritime economy. The Maitas Chiribaya, descendants of migrant highlanders, had a rather well-developed agricultural subsistence base. The Chinchorro demonstrated extreme attrition rates and a correspondingly high frequency of periapical abscesses. They were essentially caries-free and enjoyed a moderate antemortem tooth loss frequency. The Maitas Chiribaya suffered light attrition, a high caries frequency, especially at the cementoenamel junction of crown and root, and a remarkably high antemortem tooth loss frequency. The cultural practice of coca-leaf chewing is implicated in the excessive posterior edentulism of the Maitas Chiribaya.

The geographic setting of the prehistoric Chinchorro and Maitas Chiribaya (the latter hereafter referred to as Maitas) peoples was the Atacama desert. It abruptly confronts the Pacific Ocean on its western border and is paralleled on the east by the Andes mountain range, which rises 100–150 km inland to heights of 5,000 m. A lesser range, paralleling the Andes with a broad rolling highland plain (the altiplano) between them, reaches 4,000 m altitude. The Atacama desert, which lies between the Andes and the coast, is intersected by steep-walled valleys cut by melt water at the end of the Ice Age. One of these reaches the coastline as the Azapa valley.

The bold dissimilarity of northern Chile's eastern and western borders combines similar aerological dynamics to make the Atacama desert the driest place on earth. The cold antarctic water of the Peru coastal current, rich in marine biota, causes southwesterly Pacific breezes to condense their moisture at sea before reaching the coast. Easterly Atlantic air precipitates its moisture on the rain forest of Bolivia as it rises to pass over the Andes. The results of this bilateral extraction of moisture is a perpetual absence of rainfall on the Andean western slopes between 3,000 m and the Pacific Coast.

The earliest north Chilean population occupied the coastal river mouths. The preceramic (7500–2000 BC Chinchorros derived their subsistence primarily from marine resources (Aufderheide and Allison, 1992). At approximately 1000 BC highland migrants, Alto Ramirez people from Lake Titicaca, arrived at the coast and introduced agropastoralism to the area. Subsequently, successive cultures amplified the agricultural aspects culminating in the Maitas group, about AD

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1000–1250, more than half of whose diet consisted of agricultural products.

This study compares the dental condition of the earliest inhabitants of the Azapa valley, the preceramic Chinchorros, with agriculturalists, the Maitas, focusing on environmental and cultural practices in analyzing their differences. Diets had previously been estimated for both cultures using chemical analyses for bone trace mineral content and stable isotope ratios (Aufderheide and Allison, 1992; Tieszen and Chapman, 1992). Their results were made available to us for this study.

Laboratory procedures presently exist which can establish the presence or absence of cocaine in mummy hair. The practice of coca-leaf chewing is determined by hair analysis for the presence of cocaine and its metabolite benzoylecgonine by radioimmunoassay and gas chromatography mass spectrometry. A positive test reflects antemortem coca leaf exposure. These modern biochemical methods were adapted and utilized in a study of hair samples from six ancient cultures of northern Chile (Cartmell et al., 1991). That study included the Chinchorro and Maitas populations whose dentition forms the basis of this report. Thus, in addition to comparing the dental condition of the ancient preagricultural and agricultural inhabitants of the Atacama Desert, this study seeks to determine whether coca-leaf chewing had an impact on antemortem tooth loss.

MATERIALS

The skeletal material for examination was made available to our study team by the Museo Arqueologico, San Miguel de Azapa (MASMA), at the University of Tarapaca in Arica, northern Chile. Arica is at the mouth of the Azapa valley, whose river provided the water source for a succession of populations extending from the earliest Chinchorro to the modern period. Beginning at the valley's mouth, burial grounds of the ancient populations extend as far as 12–15 km inland up the valley.

Chinchorro burials were excavated from Mo-1 and Mo1-6 sites on the slopes of the northern face of the valley's southern flank. The Maitas bodies were excavated from the valley site labeled AZ-140 approximately 8 km from the coast. While some of their human remains were spontaneously mummified, soft tissue preservation was substantially less than among the Chinchorro groups.

TABLE 1. Sex, age, and average age by culture and number of individuals[1]

	Number of Individuals by Sex			Average Age by Sex		
Culture	M	F	Total	M	F	Average age by culture
Chinchorro	20	20	40	42	32	37
Maitas Chiribaya	20	26	46	31	35	33
Total individuals	40	46	86	36.5	33.5	35

[1] Age and average age are in years.

Eighty-six adults, representing 40 Chinchorros and 46 Maitas, were examined for dental pathology. Sex determination was based on traditional diagnostic cranial sex traits (Krogman and Iscan, 1986). Age estimates were based on tooth eruption, and attrition rates (see below) were correlated with anthropological estimates on file in the museum records.

The Chinchorro sample consisted of 40 maxillae and 35 mandibles, equally represented by sex. Their average age at death is 37 years. The Maitas, representing 19 males and 27 females, consisted of 46 maxillae and 45 mandibles. Their average age at death is 33 years (Table 1).

METHODS

Data were collected for all tooth sites: sites with teeth present, empty sockets due to postmortem tooth loss, and healed sockets representing teeth lost antemortem. Data from each site is recorded by tooth type, class, quadrant, and dental arch. Dental pathology frequency is calculated as a percent of the total number of tooth sites available for examination for the feature studied. The total number of tooth sites is the sum of 1) fully erupted teeth present, 2) partially erupted teeth present, 3) impacted teeth present, 4) teeth congenitally missing, 5) teeth lost antemortem, and 6) teeth lost postmortem (Table 2).

Numerical differences between group comparisons were evaluated by chi-squared analysis and, in the comparisons with coca-

TABLE 2. Number of tooth sites available for examination

	Chinchorro	Maitas Chiribaya	Total study
Number of teeth present			
In functional position	868	948	1,816
Partially erupted	6	22	28
Impacted	1	4	5
Total present	875	974	1,849
Number of teeth missing			
Congenitally missing	17	37	54
Lost antemortem	114	222	336
Lost postmortem	188	226	414
Total missing	319	485	804
Total teeth sites possible	1,194	1,459	2,653

leaf chewing, relative risk estimate with 95% confidence limits. The term *statistically significant*, as used in this study, indicates that the chance probability of the demonstrated differences is less than 5%.

Attrition

Brothwell's (1981) attrition scale was modified to apply to all teeth and adjusted to differentiate clearly between physiological attrition (0–4) and pathological attrition (5–8) as indicated below. Pathological attrition is defined as loss of tooth vitality through pulp exposure and localized destruction of interdental periodontium due to loss of proximal tooth contact. The scoring method identifies the following degrees of attrition:

Stage 0. No discernible wear facets in enamel.
Stage 1. Enamel only; wear facets visible.
Stage 2. Dentin spots appear at cusp tips or incisal edges.
Stage 3. Large areas of cuspal or incisal edge dentin are exposed; secondary dentin may appear.
Stage 4. 1) Premolars: two areas of cuspal dentin are exposed.
2) Molars: two or more areas of cuspal dentin are exposed.
3) Incisors and canines: entire incisal edge or cuspal base is exposed dentin.
4) No pulp exposure or proximal contact lost.
Stage 5. Begins wear of pathologic potential.
1) A thin ring of enamel surrounds biting surface.
2) Primary and secondary dentin exposed; proximal contact lost.
Stage 6. 1) Pulp chamber is open; root canal exposed.
2) Pulp chamber exposed; proximal contact is lost.
Stage 7. Severe helicoidal attrition pattern in which centric cusp roots become chewing surfaces (posteriors).
Stage 8. Crown completely worn away; root only in function.

Caries

Dental caries classification may be divided into two general categories based on the elemental structure of the tooth surface exposed to the carious processes. These are crown (enamel) caries or root (cementum) caries. Crown caries usually originates in developmental pits and fissures and less commonly on smooth surface enamel. Root caries commonly begins at the cementoenamel junction of the crown and root, although root furcations are also vulnerable in early stages of exposure. Caries data is recorded by surface aspect and anatomic features at the site of caries initiation. Large lesions of indeterminate origin which involve extensive areas of both crown and root are scored as one crown lesion and one root lesion.

Alveolar osteitis

Evidence of alveolar osteitis in skeletal material is identified by its location, pattern, and degree of bone destruction. It may be characterized by horizontal or linear bone

TABLE 3. Comparison of antemortem posterior (only) tooth loss (AMTL) by culture and age[1]

	Age (years)								All ages[2]	
	20–29		30–39		40–49		50+			
	Ch	Ma	Ch	Ma	Ch	Ma	Ch	Ma	Ch	Ma
Number of posterior AMTL	0	12	11	24	32	58	23	85	66	179
Number of posterior sockets examined	47	219	220	220	230	160	140	160	637	759
Chi square	1.5750 (y)		5.2459		26.5214		43.6407		41.8465	
df	1		1		1		1		1	
P	.2095		.0220		.0000		.0000		.0000	

[1]Ch = Chinchorro; Ma = Maitas; y = Yates factor corrected.
[2]Includes only those 20+ for whom age is known.

loss as a sequel to generalized periodontal disease or by localized, tooth-related vertical loss of tooth attachment bone. Localized, dentition-related alveolar osteitis occurs along two basic pathways: from within the tooth as an extension of pulpal inflammation creating an abscess in periapical bone or as an extension of periodontal attachment inflammation originating outside of the tooth (Carranza, 1984).

Tooth-specific abscesses are classified as periapical or periodontal based on the site of origin and the pathway of extension in the alveolar bone. I employed seven features identifiable in skeletal material to describe localized dentition-specific alveolar osteitis. Features of periapical abscesses are 1) the pulp chamber exposed with periapical fistula or 2) the pulp chamber exposed with no fistula visible, with features of periodontal abscesses are 3) alveolar bone loss within root furcation, 4) interproximal crater formation, one site, two teeth, 5) interproximal cratering, two sites, three teeth, 6) advanced circumferential vertical bone loss, and 7) massive bone loss and periapical and periodontal abscesses in combination.

Antemortem tooth loss

Antemortem tooth loss (AMTL) is a nonspecific indicator of past pathology. It provides a background against which existing pathology may be compared in search of correlations. For this reason, AMTL frequency was compared with existing dental pathology frequencies by tooth type, tooth group and age. Pathologic changes were viewed within functional tooth groups—that is, anterior (biting teeth—incisors and canines) and posterior (chewing teeth—premolars and molars)—because dental pathology is also related to differing functional requirements of tooth form. The loss of posterior teeth in the Chinchorro and Maitas groups was examined by age decade (Table 3). The exact comparison was between AMTL and no AMTL in the given age range. When required, Yates's continuity corrected chi square was employed. Finally, the information on antemortem coca use by individuals in the study samples (Aufderheide and Allison, 1992) was used to compare AMTL in coca-leaf chewers vs. nonchewers. The confidence interval for the relative risk estimate of AMTL in coca-leaf, chewers was also obtained (Schlesselman, 1982).

RESULTS

Dental pathology includes a variety of disease conditions which affect teeth and their supporting tissues. Dental diseases seldom act in isolation but over time act and react synergistically, creating complex patterns of destruction that require meticulous scrutiny for proper reconstruction of their chronology.

The comparison of antemortem tooth loss (AMTL) (Fig. 1) demonstrates that the Maitas suffered significantly higher AMTL (n = 222) than the Chinchorros (n = 114) ($\chi^2 = P < .05$). The value of examining dental pathology by tooth type becomes apparent in Table 4, which reveals that the statistically significant AMTL difference between the cultural groups was due primarily to the differences in AMTL of the molars. Chi-squared values for each tooth type reveal probability values of $P < .05$ for the molars only.

The age-progressive nature of AMTL and dramatic cultural differences in frequency are visually apparent in Figure 2. The differ-

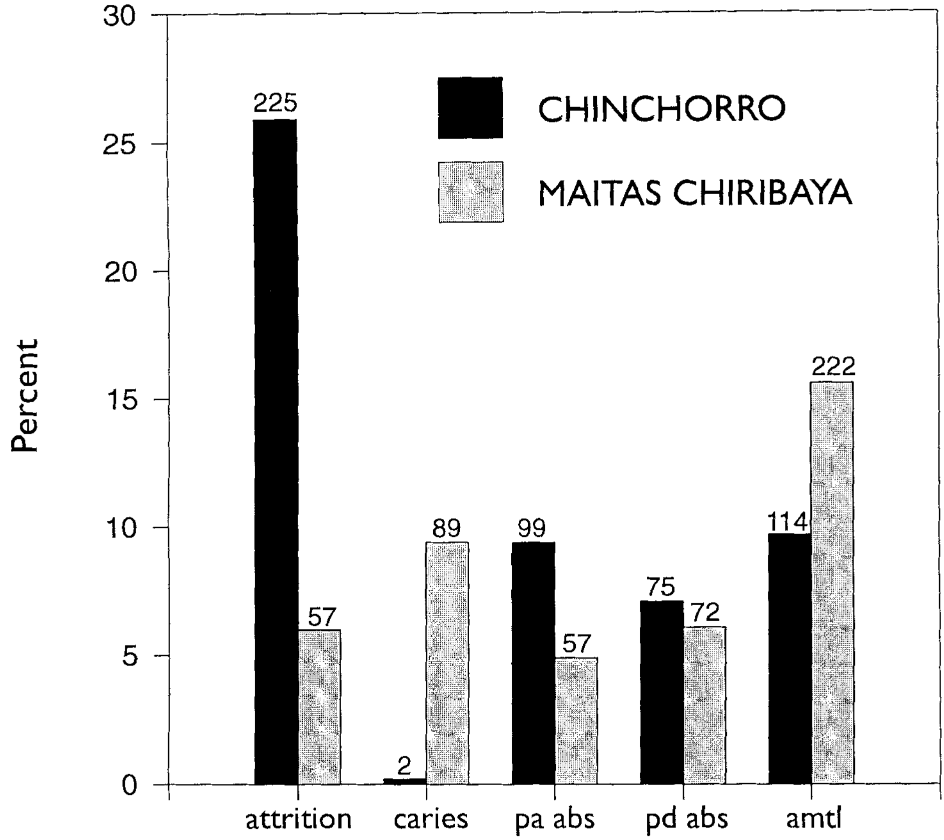

Fig. 1. Frequencies of dental pathology and antemortem loss by cultural group. amtl = antemortem tooth loss; pa abs = periapical abscess; pd abs = periodontal abscess. Values for pathological degrees of attrition and for caries are based on the total number of teeth present, while the remaining categories are based on the total number of tooth sites studied. The numbers on the bars show the number of teeth affected by the indicated pathological process.

TABLE 4. Comparison of total antemortem tooth loss (AMTL) by culture and tooth type[1]

	Tooth type															
	I1		I2		C		PM1		PM2		M1		M2		M3	
	Ch	Ma	Ch	Ma	Ch	Ma	Ch	Ma	Ch	Ma	Ch	Ma	Ch	Ma	Ch	Ma
Number of teeth AMTL	27	20	15	13	5	6	7	15	16	24	10	44	13	53	20	44
Number of sockets examined	148	182	148	182	149	182	149	182	149	182	149	182	150	182	150	180
Chi square	3.5168		.9412		.0009		1.6582		.4623		18.3029		21.5994		6.4615	
df	1		1		1		1		1		1		1		1	
P	.0608		.3320		.9762		.1978		.4965		.0000		.0000		.0110	

[1]C = canine; Ch = Chinchorro; I = incisor; M = molar; Ma = Maitas; PM = premolar.

ences in the Chinchorro and Maitas values for AMTL for posterior teeth of each decade were compared by the chi-squared method. This revealed a χ^2 value for $P > .05$ for the 20–29 decade but $P < .05$ for each of the three succeeding decades.

Hair analysis of the Chinchorros indicated an absence of cocaine, unlike the findings in

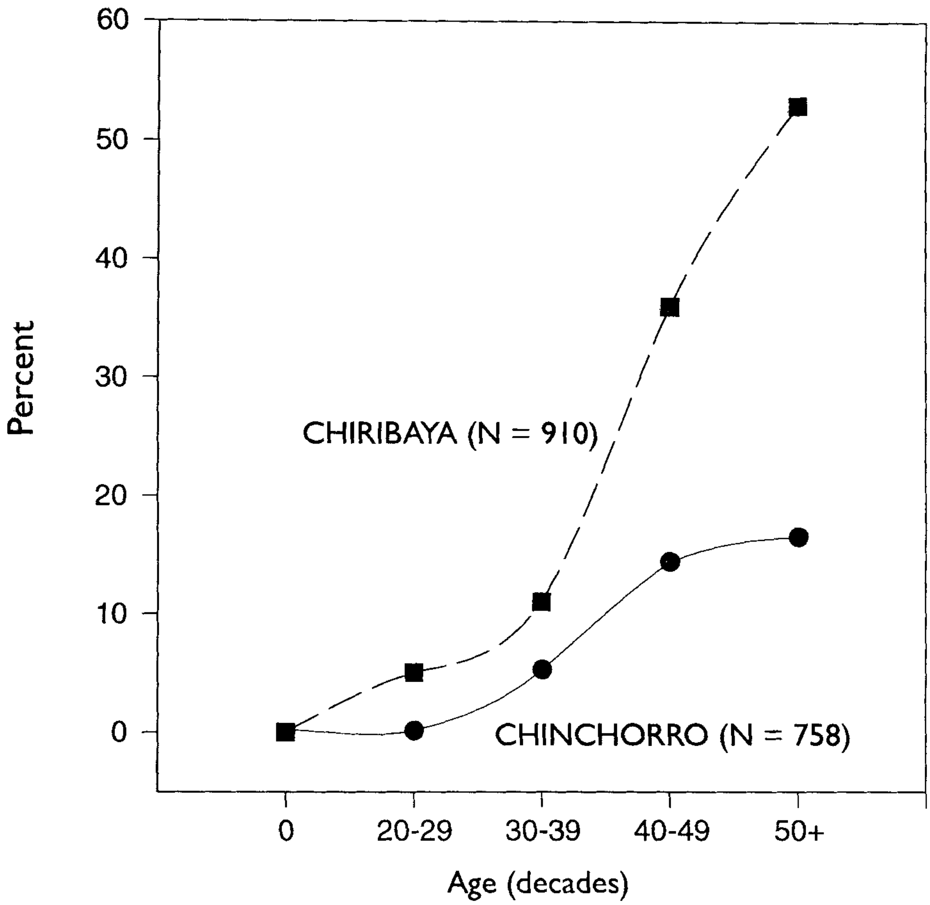

Fig. 2. Comparison of antemortem loss of posterior teeth by age decades. Differences above age 29 are statistically significant (see Table 3). N values represent the number of posterior teeth possible in the studied sample.

the Maitas sample (Aufderheide and Allison, 1992). Among the Maitas, the difference in AMTL between chewers and nonchewers of coca leaves is significant (Table 5). The difference is also apparent by age.

Attrition

Attrition, the physiologic wearing away of tooth hard tissue as a result of tooth-to-tooth contact, becomes pathological only when tooth vitality and/or alveolar bone are adversely affected. This can occur when tooth wear exceeds the physiologic capacity of body defense mechanisms to 1) protect tooth vitality by deposition of secondary dentin in the pulp chamber or 2) remodel alveolar bone at a rate sufficient to maintain tooth contact lost due to proximal surface wear (Carranza, 1984). Cultural frequencies of pathologic attrition are shown in Figure 1. The number of teeth with attrition scores in the pathological range are fourfold greater among the Chinchorros (n = 225) than among the Maitas (n = 57). When pathologic attrition is further examined by individual tooth type (Fig. 3), it is apparent that, with the exception of third molars, all tooth types shared in the remarkable cultural difference in pathological attrition.

Caries

Dental caries is a multifactorial disease of the calcified tissues of teeth characterized by demineralization of the inorganic portion

TABLE 5. Comparison of total antemortem posterior (only) tooth loss (AMTL) by coca chewing and age among Maitas only[1]

	Age (years)									
	20–29		30–39		40–49		50+		All ages[2]	
	Chewers	Nonchewers	Chewers	Nonchewers	Chewers	Nonchewers	Chewers	Nonchewers	Chewers	Nonchewers
Number of posterior AMTL	2	6	6	12	38	0	57	2	103	20
Number of posterior sockets examined	99	60	80	60	60	20	80	20	319	160
Chi square	3.4486 (y)		4.7814		24.1270		24.8140		21.8631	
df	1		1		1		1		1	
P	.0633		.0288		.0000		.0000		.0000	
Relative risk estimate	0.186		0.324		Undefined		22.304		3.338	
95% confidence limits	0.036–0.951		0.114–0.922		Undefined		4.786–103.9		2.590–7.195	

[1] Hair analysis of Chinchorros showed an absence of cocaine (Aufderheide and Allison, 1992) (see text). y = Yates factor corrected.
[2] Includes only those for which age and coca use are known.

and destruction of the organic portion. Although many aspects of its etiology are still obscure, two principal theories have evolved: the acidogenic and proteolytic (Shafer et al., 1983). However, there is no universally accepted opinion as to which is correct.

Initiation of a carious process on any tooth surface requires that the surface be exposed to oral fluid and its microbial content. Normally, only the enamel-covered crown of a functioning tooth is so exposed and at risk of an initiating carious process. Root caries, on the other hand, can occur only after root surfaces have lost their connective tissue attachment (Hazen et al., 1973). It is apparent that tooth crowns are vulnerable to caries from the time of eruption, while caries of the root occurs later in life after a tooth's investing and supportive periodontium has been compromised by another disease process that exposes root surface to the oral microbiota.

In view of the host age differences at which caries of the crown and caries at the root are likely to be initiated, as well as the dissimilar composition of enamel, cementum, and dentin, it follows that it can be useful to consider crown caries and root caries as separate entities when predicting circumstances which lead to carious lesions.

Caries data revealed a striking contrast in prevalence by culture. One-half of the Maitas individuals suffered dental caries compared to only one of the Chinchorros. In terms of numbers of carious teeth, the difference is fortyfold (89 vs. 2) (Fig. 1). Normally this striking difference in caries frequency would be attributed to the high carbohydrate fraction of the Maitas diet compared with the predominately marine nature of the Chinchorro diet (Aufderheide and Allison, 1992). However, elsewhere in this manuscript I suggested that carbohydrate plays an etiological role in crown caries only. It this study, however, 79 (82%) of the 89 Maitas carious teeth had root lesions, and only 16 involved tooth crowns (Fig. 4).

Thus, the bulk of carious lesions occurred on the root, and root caries occurs after destruction of its overlying tissues. These observations imply that caries is not the primary cause of the observed excessive posterior tooth loss and compels us to shift

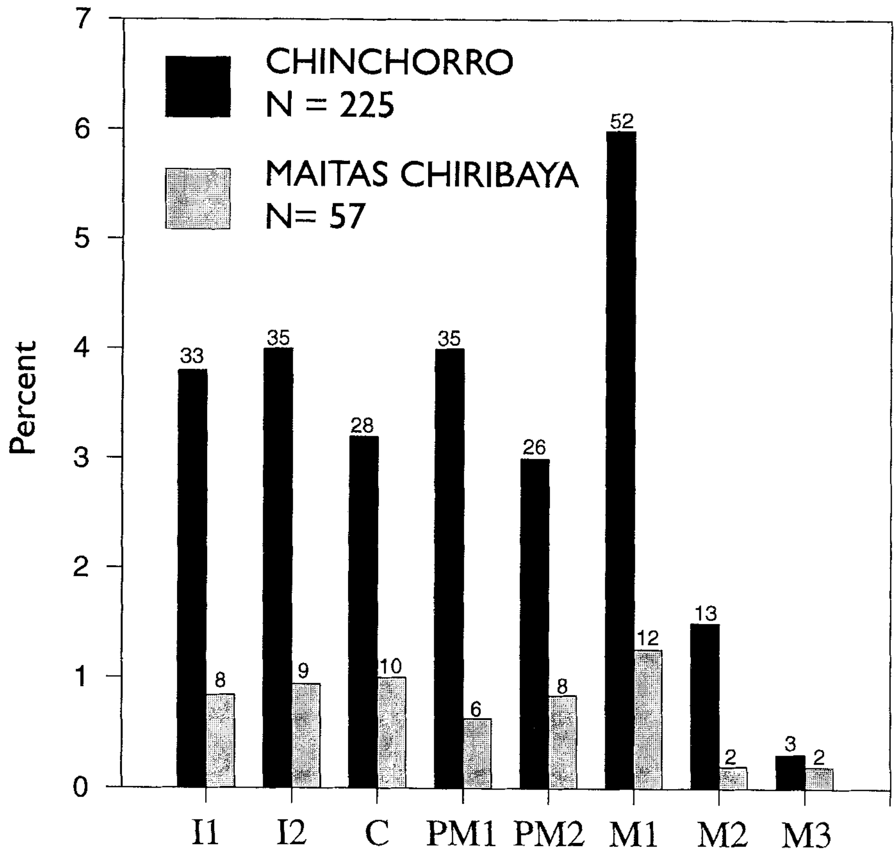

Fig. 3. Comparison of Chinchorro and Maitas pathologic attrition scores by tooth type. Numerical values on the y axis represent the fraction of teeth showing pathological degrees of attrition expressed as percent of all teeth available for study. The numbers on the bars for each tooth type indicate the number of teeth affected by pathological tooth attrition.

our search for its etiology to the causes of the periodontal destruction.

Alveolar osteitis (periodontitis)

A generalized horizontal reduction in alveolar crest height, as occurs with chronic gingival inflammation, was not apparent in either culture. Only localized tooth-specific alveolar osteitis was observed and recorded as periapical and periodontal abscesses. Attrition, caries, and trauma were the principal causes of these abscess types for both populations.

The Chinchorros registered a high periapical abscess frequency (n = 99) which correlates positively with its severe attrition rate (n = 225) (Fig. 1). Despite the exposed pulp chambers and periapical alveolar bone involvement resulting from the extensive attrition, the teeth so involved still retained excellent bone support and were able to continue functioning. Periapically abscessed, multirooted teeth generally escaped postmortem loss as well.

The Maitas, on the other hand, had a modest periapical abscess frequency which numerically matched their attrition frequency (n = 57).

The traditional forms of localized, tooth-specific periodontal abscess were of moder-

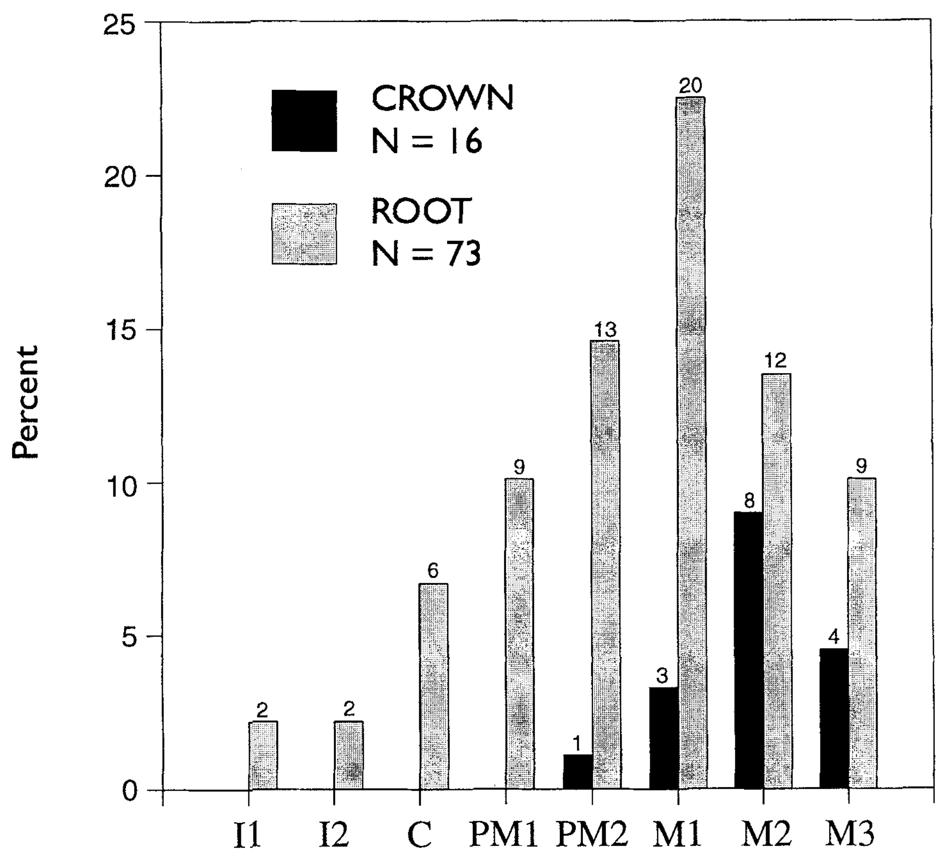

Fig. 4. Comparison of Maitas Chiribaya crown and root caries frequencies by tooth type. C = canine; I = incisor; M = molar; PM = premolar. Distribution and frequency of Maitas teeth showing crown caries and those with root caries expressed as a percentage of total carious teeth. The numbers on the bars indicate the number of teeth affected by the type of caries indicated.

ate and essentially equal frequency among both cultural groups. Inasmuch as chronic and progressive loss of periodontal attachment tissues must precede tooth loss, the modest periodontal abscess frequency of the Maitas does not explain their extreme antemortem loss frequency (n = 222), especially of the posterior teeth (Fig. 2), which is nearly double the AMTL frequency of the Chinchorros (n = 114).

DISCUSSION

This remarkable dichotomy of pattern and antemortem tooth loss experienced by the Maitas and the Chinchorros is the focus for my analysis of their dental pathology. However, before the cause of the observed difference can be attributed to a specific phenomenon—for example, coca-leaf chewing rather than the carbohydrate content of an agrarian diet—it must first be shown why carbohydrate consumption provides an inadequate explanation.

Antemortem tooth loss

As a background for interpreting the sequence of and synergy between the major pathologic conditions contributing to antemortem tooth loss (AMTL), a brief review of the structures which fix teeth in their sockets is in order.

Teeth are not actually fixed in bone (ankylosed) but are suspended in a slightly oversized socket (alveolus) within the alveolar

processes of the jaws. Attachment between root cementum and the cribriform cortical bone lining the socket is accomplished by a connective tissue membrane (periodontal ligament). Space for the ligament varies from 0.15–.40 mm (Gartner, 1982). Functional tooth movements within this space stress ligament fibers providing the stimulation necessary to trigger the bone remodeling needed to compensate for tooth surface lost as a consequence of physiologic wear. The ligament's meshwork houses cells (cementocytes and osteocytes) with the capacity to form new cementum or new bone. It is nourished by a rich anastomosing vascular network which also connects with the vessels entering the apical foramen into the tooth's pulp canal. Sensory tactors of the parasympathetic nervous system course through the periodontal membrane monitoring occlusal forces to prevent traumatic injury to the tooth or its periodontium (Morrey and Nelsen, 1970).

Tooth-supporting tissues (alveolar bone, periodontal ligament, and cementum) as well as the investing gingiva collectively make up the periodontium. As long as the periodontium is intact and healthy, a tooth remains in situ whether the pulp is vital or not. Modern dentists exploit this inner-outer vitality feature in root canal procedures by reaming, sterilizing, and sealing off a nonvital pulp canal from a vital periodontal ligament in order to preserve a tooth for further function. Without such intervention, osteoclasts of the macrophage system will create a fistula through the thin cortical alveolar bone at the root apex to attenuate the pulpal inflammation and disperse its noxious byproducts into the oral cavity, thus obviating the spread of inflammation into the periodontal ligament space. It appears that the highly vascular periodontal membrane plays an important role in this defensive action. As long as the periodontal membrane remains vital and intact, tooth exfoliation is not a likely consequence of pulp exposure alone (Koritzer, 1968).

Although pulpal inflammation may spread coronally within the periodontal ligament or exit the pulp canal through an anomalous accessory foramen (Clark, 1993), the findings of this study identify periapical fistulization as the preferred route for the dispersion of the noxious byproducts of pulp exposure. Eighty-two percent of the pulp exposures affected periapical bone only; the remaining 18% were combinations of periapical and periodontal abscesses of such magnitude that an exact determination of initial inflammation could not be determined.

The majority of uncombined periodontal abscesses, however, originated at interdental crestal bone sites and were associated with faulty proximal contacts, in some cases associated with tooth movement following loss of adjacent or opposing teeth and in a number of cases associated with congenitally missing or malformed teeth. The majority of the localized periodontal abscesses, however, were associated with attrition-related faulty tooth contact. Contact loss from severe attrition can occur because of the specialized anatomy of the contacting surfaces of all human teeth. The mesiodistal tooth diameters are greater at the contact area than at the cervical areas. This difference provides space for the interdental gingiva to seal and protect the underlying tooth supporting tissues. Lack of contact exposes the interdental gingiva to traumatic packing, stagnation, and putrefaction of food. Acutely inflamed gingiva attracts opportunistic microorganisms whose metabolic products expand the inflammation into the supporting connective tissues. Protected by the wide faciolingual diameters of posterior teeth, the inflammation is provided the isolation time necessary to become chronic. Inflammatory advance into the supporting periodontium forms vertical defects between tooth root and alveolar bone. At the leading edge of the advancing defect (pocket), subgingival calculus forms on the cementum of the root. As more root is exposed, root (cementum) caries often follows as a complication of an already serious periodontal disease (Williams, 1990).

Considering the fact that root caries develops on the trailing edge of periodontal pocket formation which likely began after years of mastication, it is not surprising that root caries is a disease of older adults (>30 years). By contrast, crown caries commonly

originates in the developmental pits and fissures present in the unworn enamel of subadults and young adults.

Most investigators agree that any search for causes of AMTL in skeletal material must include all identifiable dental pathology. There is also general consensus that the primary causes are found within three major categories of dental diseases: attrition, caries, and periodontal disease.

Armelagos and Rose (1972) observed a pattern of temporal change in the relative importance of these pathologic conditions in terms of AMTL. In a study of prehistoric Nubians, they found that attrition was the most important factor among the Mesolithic populations. In the later Meriotic period, caries became the leading feature, while periodontal disease predominated among the late Christian populations.

A clear sequence within the synergy of actions between disease categories is not easily established in skeletal samples which have exceptionally high AMTL rates. In a study of the dental pathology among inhabitants of the lower Pecos region of Texas, Hartnady and Rose (1991) observed AMTL so extensive that assessment of the tooth-supporting periodontium was an exercise in futility. They were obliged to use a two-stage model of caries and attrition only in their deliberations. The limitations of a two-stage model were encountered immediately. The few teeth available for examination experienced high rates of attrition as well as caries despite the fact that severe attrition can be expected to reduce the number of caries-susceptible areas on occlusal enamel of tooth crowns. Severe attrition can also promote root caries. However, even though no root caries was reported, caries was implicated as the primary cause of the extensive edentulism on the basis of a high carbohydrate diet.

In a comparative study of tooth loss rates between an agricultural and a hunter-gatherer population of the Tennessee Valley, Smith (1987) reported that AMTL was highest among the agricultural population and attributed the loss to their high caries frequency. No distinction was made relative to the anatomic location of the caries. Kelley et al. (1991) examined, along with other regional groups, the same Maitas skulls being reported in this paper. They concluded that the Maitas's high carbohydrate diet was probably responsible for their elevated caries rate, though some inconsistencies in their data led them to explore other possibilities including trace element content differences. The Kelley data also makes no distinction between crown caries and root caries relative to the site of initiation of the carious process.

Root caries is a defining factor in the age-progressive nature of dental caries. It was common in ancient humans, often occurring in the absence of crown caries (Langsjoen, 1995). A number of early investigators have reported a high prevalence of root caries in antiquity. In an expansive report on dental and alveolar infection, Moore and Corbett (1983) cites Hardwick's study of dental caries patterns among the sixth-century Saxons and contemporary Britons. Hardwick observed not only that the modern English experienced six times the caries rates of the Saxons, but he also noted a sharp difference in the distribution of the lesions. He found that the majority of cavities were located in enamel pits and fissures or contact areas of the crown in the modern population in contrast to the Saxon population, in which nearly all of the carious lesions were located at the cementoenamel junction of root and crown. This distribution pattern has been reported for many ancient populations, including the Roman Britons, the medievel Swedes, pre-Columbian Peruvians, aboriginal Americans, and ancient Egyptians.

Root caries and crown caries are similar to the extent that the result of either process is destruction of tooth hard tissue. The differences, however are abundant: 1) the site on the tooth at which the process begins; 2) the elemental composition of tissues affected; 3) the age of the host at the onset of the carious process; 4) the position in the sequence of other dental diseases; and 5) the predominant bacterial types involved, their preferred substrate, and the chemical nature of their metabolic byproduct (i.e., aciduric or proteolytic).

These fundamental differences in crown caries and root caries, if unrecognized, have a confounding effect on interpretation of data. Thus, it is important to record with accuracy the initiation sites of carious le-

TABLE 6. Location and chronology of dental pathology mechanisms

Pathology	Site	Age at expression	Effect
Attrition	Occlusal surface	Mid to late	Pulp exposure
	Proximal surface	Mid to late	Contact broken
Caries	Crown; enamel and dentin	Early	Pit and fissure decay
	Root; cementum and dentin	Late	Root decay
Periodontitis	Generalized	Mid to late	Horizontal bone loss
	Localized	Mid to late	Vertical, tooth-specific bone loss

sions. Without such information, it is speculative, for example, to conclude that the carbohydrate in an agrarian diet is the agent responsible for the high caries rate of a given population.

Investigators have often experienced frustration with the lack of specificity possible in determining cause-and-effect relationships among the big three in dental pathology: attrition, caries, and periodontal disease. Important subdivisions within each category need to be recognized (Table 6). Paradoxical as it may appear on the surface, a doubling of the number of factors to be considered should simplify the assessment of the data collected. However, in this study, though I have doubled the number of features to be considered, a positive correlation between diseases common to the oral environment and the Maitas's massive loss of posterior teeth is still lacking. The only other identifiable factor which might have adversely affected the dental condition of the Maitas and not the Chinchorros was the cultural practice of coca-leaf chewing. This possibility is investigated further below.

Coca-leaf chewing

The most highly prized product of Peruvian agriculture was the coca plant (*Erythroxylon coca*), and chewing of raw coca leaves is a common practice among Andean cultures today. Archeological evidence documenting its existence in antiquity, such as gourd containers for lime and ceramics depicting a bulging cheek, have been recovered near Arica, Chile (Lumbreras, 1974). The presence of coca leaf tomb offerings among the mummified remains from the Chiribaya sites near Ilo, Peru, and Arica, Chile, further attest to its widespread use in antiquity (Aufderheide, 1990; Cartmell et al., 1991). The primary effect of coca-leaf chewing is a mild stimulation of the central nervous system which gives a sense of increased energy, the temporary suspension of appetite, a suppression of fatigue, and a sense of well-being. It is also used to overcome altitude sickness and as a symptomatic treatment for toothache, and it has a medicinal effect on gastrointestinal disorders.

The only untoward reaction reported is the numbing effect it has on cheek and tongue thought to be due to the anesthetic properties of cocaine, one of the alkaloids extracted from the leaf by the lime or ashes which are added to alkalinize the quid. There appears to be no evidence of tolerance dependency or any deleterious effects, acute or chronic (Plowman, 1984).

The method of coca-leaf chewing is as follows. The dried leaves are placed in the mouth, one or a few at a time, and slowly moistened with saliva until they are moist and pliable. The leaves are then moved about with the tongue, rolled into a bolus or quid, and pushed into one cheek. The leaves are not really chewed, but are sucked upon to extract the bitter juices. In order to enhance extraction of the alkaloids and "sweeten the chew," a needle applicator is moistened, dipped into a gourd of lime, and carefully placed into the mouth and guided into the bolus. This is repeated several times, always with care so as not to touch the mucous membrane with the undiluted lime. The liming process is often repeated several times for the same quid and the reliming accompanied with additional coca leaves (Leigh, 1937).

The lime facilitates the release of leaf alkaloids, including cocaine, which are readily absorbed by the oral mucosa. The position of the quid (Fig. 5) in direct contact with the mucosa of the cheek as well as gingival mucosa of the posterior teeth for extended

Fig. 5. Coca quid placement. Cabuza culture, Arica, northern Chile, AD 500.

periods of time corresponds to the pattern of Maitas's antemortem molar loss which, in turn, could represent the terminal stages of the type of one-sided (buccal only) loss of alveolar bone observed by Turner (1993) in a museum sample of isolated Peruvian mandibles.

Calculus and lime

Undisturbed dental plaque mineralizes by the deposition of calcium and phosphate salts from the saliva, especially when the teeth are situated adjacent to the orifices of major salivary ducts. Salivary calculus (mineralized dental plaque) is 70–90% inorganic, two-thirds of which is in crystalline form. Its crystalline component is mainly hydroxyapatite: $Ca^{10}(PO_4)6(OH)_2$. It is a whitish, hard, clay-like mass which readily absorbs food pigment and becomes stained. It is friable and easily detached, making it an inconsistent indicator in the evaluation of horizontal bone loss in skeletal material. Lime, on the other hand, is a caustic, amorphous, cheesy solid obtained by calcining limestone, seashells, or other forms of calcium carbonate. Heating the carbonate drives off the CO_2, converting the carbonate to the caustic calcium oxide (CaO) that gives off considerable heat when exposed to water, producing calcium hydroxide ($Ca(OH)_2$). Prolonged exposure to the carbon dioxide in air restores it to the carbonate form. Depending upon the details of its preparation, "lime" employed for coca-leaf chewing undoubtedly represents a mixture of these compounds with varying concentrations of its caustic component—CaO. Conceivably, heat generated by contact of CaO with oral fluids may be detrimental to cellular integrity of the gingiva and bone, the pain of which may not be sensed by the chewer because of the local anesthetic action of cocaine. Alternatively, lime or some presently undefined component of coca leaves may destroy tissue integrity via a lytic action on collagen fibers.

The colloquial use of the term *lime* to describe calculus is misleading and inaccurate since the two compounds share a physical likeness only. Unfortunately, the terms have been used interchangeably for decades. For example, in describing the duties of dental auxiliary personnel, the dental law of Minnesota, of 1935, stated "a licensed dental hygienist may remove lime deposits, accretions, and stains" from the exposed surfaces of the teeth. The misuse of the term *lime* as a descriptor for a dental mineral deposit composed of hydroxyapatite of salivary origin has created an opportunity for serious miscommunication in circumstances that include also the employment of the chemical lime (calcium oxide [CaO]). For example, several authors report the deposition of extensive dental calculus in populations among whom the habitual chewing of botanical substances was common. Mehta et al. (1955) studied modern betel nut chewers in India. Leigh examined betel nut chewers (1929) and both Leigh (1937) and Klepinger et al. (1977) studied archaeological populations of coca-leaf chewers. All three of these authors commented on evidence of extensive dental calculus formation in these groups, though the terms *lime deposits* and *dental*

TABLE 7. Frequency and antiquity of prehistoric coca-leaf chewing practices in northern Chile[1]

Culture	Number tested	Number (%) positive[2]	Time period of sampled sites
Chinchorro	23	0 (0)	3000 BC to 1250 BC
Alto Ramirez	3	1 (33)	1000 BC to AD 350
Cabuza	16	10 (62)	AD 400 to AD 1000
Maitas Chiribaya	97	54 (56)	AD 1100 to AD 1250
San Miguel	8	2 (25)	AD 1200 to AD 1350
Inca regional chiefdom	13	9 (70)	AD 1400 to AD 1500
Totals	160	76 (47)	BC 3000 to AD 1500

[1] Abstracted from Table 1, Cartmell et al. (1991).
[2] Positive test reaction indicating the presence of cocaine or its metabolite benzoylecgonine.

calculus deposits are sometimes used as synonyms. Yet all of these populations added the chemical lime (CaO or its hydrated or carbonated forms) to the chewed botanicals. This sets the stage for the potential of a reader's misunderstanding that the dental deposit itself may be lime (CaO). Klepinger clearly demonstrated by x-ray diffraction analysis that the dental deposit has the same (predominantly hydroxyapatite) structure as does the dental calculus of salivary origin in living individuals who do not chew coca or betel nuts. Koritzer (1968) noted that such excessive dental deposits, especially those covering occlusal surfaces, commonly form when the tooth is afunctional—that is, no loner meets its opposing tooth. While several of these authors have suggested that use of the chemical lime (CaO) by the chewers somehow influences the deposition of the dental mineral deposit (calculus), no one has demonstrated that this same chemical forms the deposit itself. Continuation of the use of the term *lime deposit* for dental calculus in the literature will only serve to perpetuate and compound this confusion.

Application of hair cocaine study results

The Chinchorro, antedating the arrival of coca into northern Chile, all demonstrated negative results of hair tests designed to detect antemortem coca use. Of the 97 Maitas tested, more than half (56%) showed positive results (Table 7). Of the 46 Maitas examined for dental pathology in this study, 31 had been included in the original Cartmell cocaine study. Of the 31 tested, 20 showed positive results (65%), and 11 were negative.

Using our Maitas dental pathology database, the antemortem loss of posterior teeth of coca chewers (documented by these tests) was compared with that of nonchewers. The results demonstrated a highly statistically significant difference in posterior AMTL between chewers and nonchewers with an overall relative risk estimate of 3.3, indicating that chewers were four times as likely to lose posterior teeth as the nonchewers. Moreover, when examined by age decades, the risk rose to 22 times the likelihood after age 50, indicating that an age-progressive, positive correlation exists between coca-leaf chewing and posterior tooth AMTL among the Maitas (Table 5).

Synthesis

The Maitas, an agricultural population, suffered profound antemortem posterior tooth loss that could not be explained on the basis of attrition, caries, or the common forms of periodontal disease. The remarkable antemortem loss of posterior teeth was found to be related to coca-leaf chewing practices. While a precise biochemical mechanism of action between a quid of coca, lime and saliva, and the dental periodontium is not as yet defined, this article proposes that the habitual use of coca leaves with lime impaired the integrity of both investing and supporting periodonal tissues to a degree of severity sufficient to cause a pathologic exfoliation of the denuded teeth.

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LITERATURE CITED

Armelagos GJ, and Rose JC (1972) Factors contributing to antemortem tooth loss in populations from ancient Nubia. Am. J. Phys. Anthropol. *37:*428.

Aufderheide AC (1990) Report of field operations during dissections of mummified human remains from Chiribaya Alta and Yaral sites near Ilo, Peru. Manuscript on file in the Department of Anthroplogy, University of Chicago, and Paleobiology Laboratory, University of Minnesota, Duluth.

Aufderheide AC, and Allison MJ (1992) Chemical dietary reconstruction of north Chile prehistoric populations by trace mineral analysis. In R Gonzales (ed): Proceedings of the First World Congress on Mummy Studies, Museo Arqueologico y Etnografico de Tenerife, Organismo Autonomo de Museos y Centros, Cabildo de Tenerife, February 3–6, 1992. Tenerife, Canary Islands: Museo Arqueologico y Etnographico de Tenerife, pp. 451–462.

Brothwell D (1981) Digging Up Bones, 3rd ed. Ithaca, New York: Cornell University Press.

Carranza FA (1984) Glickman's Clinical Periodontology, 6th ed. Philadelphia: Saunders.

Cartmell LW, Aufderheide AC, Springfield A, Weems C, and Arriaza B (1991) The frequency and antiquity of prehistoric coca leaf chewing practices in northern Chile: Radioimmunoassay of a cocaine metabolite in human mummy hair. Latin Am. Antiquity *2:*260–268.

Clark N (1993) Periodontitis in dry skulls. Dent. Anthropol. Newsletter *7:*1–3.

Gartner LP (1982) Essentials of Oral Histology and Embryology: Reisterstown, MD: Jen House Publishing Co.

Hartnady P, and Rose JC (1991) Abnormal tooth-loss patterns among Archaic-Period inhabitants of the lower Pecos Region, Texas. In MA Kelley and CS Larsen (eds.): Advances in Dental Anthropology. New York: Wiley–Liss, pp. 267–278.

Hazen SA, Chilton NW, and Mumma RD Jr. (1973) The problem of root caries. J. Am. Dent. Assoc. *86:*137–144.

Kelley MA, Levesque DR, and Weidl E (1991) Contrasting patterns of dental disease in five early northern Chilean groups. In MA Kelley and CS Larsen (eds.): Advances in Dental Anthropology. New York: Wiley-Liss, pp. 203–213.

Klepinger L, Kuhn JK, and Josephus T (1977) Prehistoric dental calculus gives evidence for coca-chewing in coastal Ecuador. Nature *269:*506–507.

Koritzer RT (1968) An analysis of the cause of tooth loss in an ancient Egyptian populations. Am. Anthropol. *7:*550–553.

Krogman WM, and Iscan MY (1986) The Human Skeleton in Forensic Medicine. Springfield, IL: Charles C. Thomas, pp. 103–243.

Langsjoen OM (1992) Dental pathology among the prehistoric Guanches of the island of Tenerife. In R Gonzales (ed): Proceedings of First World Congress on Mummy Studies 1992, Tomo 1, Museo Arqueologico y Etnographico de Tenerife, Ogranismo Autonomo de Museos y Centros, Cabildo de Tenerife. Tenerife, Canary Islands: Museo Arqueologico y Etnographico de Tenerife, pp. 79–92.

Leigh RW (1929) Dental morphology and pathology of pre-historic Guam. Mem. Bernice P. Bishop Mus. *11:*3–19.

Leigh RW (1937) Dental morphology and pathology of pre-Spanish Peru. Am. J. Phys. Anthropol. *22:*290.

Lumbreras LG (1974) The Peoples Cultures of Ancient Peru. B.J. Meggers, trans. Washington, DC: Smithsonian Institution.

Mehta FS, Sanjana MK, Berreto MA and Doctor R (1955) Relation of betel leaf chewing to periodontal disease. J. Am. Dent. Assoc. *50:*531–536.

Moore WJ, and Corbett ME (1983) Dental and Alveolar Infection. In G.D. Hart (ed.): Disease in Ancient Man, An International Symposium. Toronto, Canada: Clark Irwin, p. 141.

Morrey LW, and Nelsen RJ (1970) Dental Science Handbook: A Joint Project of the American Dental Association and the National Institute of Dental Research. DHEW Publication No. (NIH). Washington, DC: US Govt. Printing office, pp. 72-336.

Plowman T (1984) The origin, evolution and diffusion of coca, *Erythroxylum* spp., in South and Central America. In D Stone (ed) PreColumbian Plant Migration. Papers of the Peabody Museum of Archaeology and Ethnology, Vol. 76. Cambridge: Harvard University Press.

Schelesselman, JJ (1982) Case-Control Studies: Design, Conduct, Analysis. Oxford: Oxford University Press, p. 179.

Shafer WG, Hine MM, and Levy BM (1983) Oral Pathology. Philadelphia: W.B. Saunders Co.

Smith MO (1987) Pattern of antemortem tooth loss between selected aboriginal populations of the Tennessee Valley area. Tennessee Anthropol. *12:*128–138.

Tieszen LL, and Chapman M (1992) Carbon and nitrogen isotopic status of the major marine and terrestrial resources in the Atacama desert of northern Chile. In R Gonzales (ed): Proceedings of the First World Congress on Mummy Studies, Museo Arqueologico y Etnografico de Tenerife, Organismo Autonomo de Museos y Centros, Cabildo de Tenerife, February 3–6, 1992. Tenerife, Canary Islands: Museo Arqueologico y Etnographico de Tenerife, pp. 409–426.

Turner CG (1993) A prehistoric Peruvian pathology suggesting coca chewing. Dental Anthropol. Newsletter *7:*10–11.

Williams RC (1990) Medical progress—periodontal disease. N. Engl. J. Med. *322:* 373–382.